

In-flight stability analyses applied to the Clouds and the Earth's Radiant Energy System scanning thermistor bolometer instruments on the Terra satellite

Peter Spence^{*a}, Kory Priestley^{**b}, Susan Thomas^{*a}

^a Science Applications International Corporation (SAIC); ^b Atmospheric Sciences, NASA Langley Research Center

ABSTRACT

Clouds and the Earth's Radiant Energy System (CERES) is an investigation into the role of clouds and radiation in the Earth's climate system. Two CERES scanning thermistor bolometer instruments are aboard the Earth Observing System (EOS) Terra satellite that was launched 18 December 1999. Each CERES instrument has three sensors that measure in distinct broadband radiometric regions: the shortwave channel (0.3 – 5.0 μm), total channel (0.3 – $>100\ \mu\text{m}$), and window channel (8 – 12 μm). Two analyses have been implemented to aid in monitoring the stability of the measurements of the instruments. One analysis is a three-channel inter-comparison of the radiometric measurements for each instrument. This procedure derives an estimate of the shortwave portion of the total channel sensor radiance measurement. The second analysis is a direct comparison of temporally synchronized nadir measurements for each sensor of the two instruments. Use of these analyses indicates that the shortwave region of the measurements is drifting over mission lifetime for both instruments. A discussion of correcting the shortwave drift using ground software is included.

Key Words: CERES, Terra, shortwave radiance, stability, nadir footprints

1. INTRODUCTION

The long-term goal of the CERES project is to obtain understanding of the role of clouds in the radiation budget of planet Earth.¹ Currently five CERES instruments are on three satellite platforms in Earth orbit. The CERES prototype flight model (PFM) instrument is aboard the Tropical Rainfall Measuring Mission (TRMM) satellite launched in November 1997.² Two CERES instruments, flight model 1 (FM1) and 2 (FM2) are aboard the Earth Observing System (EOS) Terra satellite launched in December 1999. And flight model 3 (FM3) and 4 (FM4) are on the EOS Aqua satellite launched in May 2002. A voltage regulator failed on PFM after the instrument provided eight months of radiance measurements and PFM is no longer operational. Analyses discussed here are restricted to the radiance measurements by the FM1 and FM2 instruments on the Terra platform.

Each CERES scanning thermistor bolometer instrument measures in three broadband radiometric regions: the shortwave (0.3 – 5.0 μm), total (0.3 – $>100\ \mu\text{m}$), and window (8 – 12 μm). Each sensor measures filtered radiance. Filtered radiance is the radiance absorbed by the sensor and has not been adjusted for optical effects of the sensor lens assembly.² The filtered radiance is converted to unfiltered radiance with ground software using the spectral response function associated with each sensor. The spectral response function is dependent on the spectral reflectance, spectral absorptance, and spectral transmission of each sensor.³ The unfiltered radiance is the radiance incident to the instrument aperture. Once in flight, the sensors are regularly calibrated using known sources. A tungsten lamp is used as a constant source for the shortwave sensor and blackbodies are used as constant sources for the window and total detectors.² In addition to the on orbit calibrations on the instruments, algorithms using ground software have been developed which can indicate stability of instrument measurements. Use of these algorithms has shown that

* peter.l.spence@saic.com; phone 757 825 7024; fax 757 825 9129; 1 Enterprise Parkway, Suite 300, Hampton, VA 23666; ** k.j.priestley@larc.nasa.gov; phone 757 864 8147; fax 757 864 7996; Atmospheric Sciences, NASA Langley Research Center, Hampton, VA 23681

there has been a drift in the ground-calibrated characteristics of the sensors. Further, this drift is occurring in the shortwave region of the measurements. Two analyses have been implemented that identified this drift, a three-channel inter-comparison of the three radiometric channels per each instrument and a direct comparison of temporally synchronized nadir measurements between each sensor of the two instruments. The three-channel inter-comparison has shown that either the shortwave sensor or the shortwave portion of the total channel sensor has drifted from its ground-calibrated characteristics for both instruments. The direct comparison shows that the two shortwave sensors compare between the two instruments. Further, in-flight calibrations indicate that the shortwave sensors for both instruments are not drifting. These analyses along with ground and on orbit calibrations were used to isolate the drift as occurring in the shortwave region. This paper will outline the analyses, present further investigation into the shortwave drift problem, and discuss methods for correction using ground software.

2. ANALYSES

2.1 Three-Channel Inter-comparison Using Deep Convective Clouds

The three-channel inter-comparison is done on the measured radiance of nadir views of Deep Convective Clouds (DCC) for the three sensors on each instrument. A theoretical basis for the three-channel inter-comparison is in reference 2. DCC are identified using the window sensor radiance equivalent to brightness temperatures less than 215 K. Multiple nadir footprints occurring in succession meeting the “cold” (215 K) brightness temperature criteria are grouped as a DCC. At least two footprints are required for DCC. Radiances, fluxes, and geolocation of the footprints comprising a DCC are averaged over all the footprints yielding one radiance, flux, and geolocation per DCC. Further, sampling is restricted to between 35 degrees north and south latitude and less than 60 degrees solar zenith with respect to the footprint. The standard deviation of the window radiance was calculated for each group of footprints comprising a DCC. Most standard deviations were less than 10 percent of the window radiance average. Some standard deviations reached on the order of 25 percent of the window radiance average. However, no DCC points were discarded due to large standard deviations of the window radiance.

Using nighttime averaged radiances of each DCC, a correlation between the nighttime window filtered radiance and nighttime total (longwave) filtered radiance is derived. This relationship is nearly linear for these “cold” footprints. Figure 1 illustrates the linear relationship between the nighttime filtered window radiance and the nighttime filtered total radiance for March 2000 measured by the FM1 instrument. The regression coefficient for a linear relationship is 0.957 and the variance is $0.159 \text{ (watt/m}^2\text{/str)}^2$ which are typical values for all months processed.

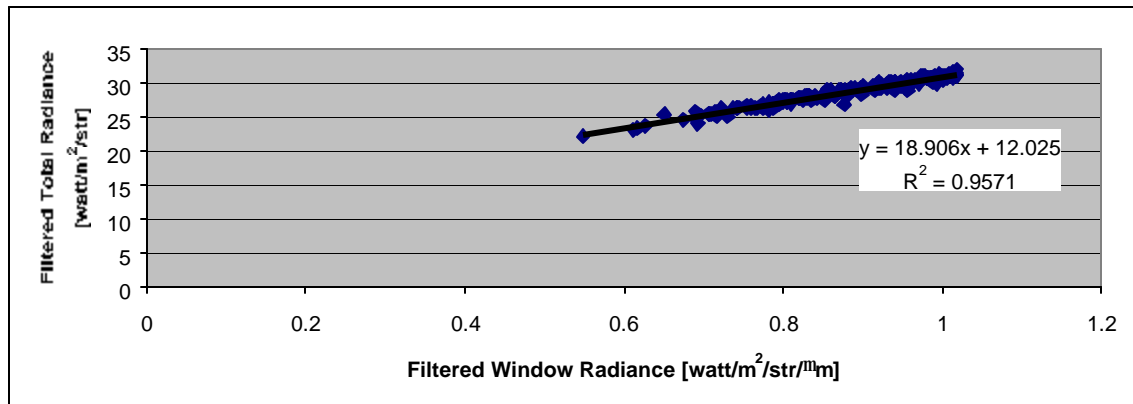


Figure 1: Correlation between filtered window radiance and filtered total radiance for nighttime DCC in March 2000 detected by FM1.

The resulting regression coefficients are used to generate a derived daytime longwave using the window channel. This derived longwave is subtracted from the total channel to obtain the shortwave portion of the total channel. Performed monthly, the resulting derived shortwave portion of the total channel is linearly correlated with the shortwave channel measurements. By fixing the intercept of this linear correlation to

zero, the resulting slope is a ratio of the shortwave portion of the total channel to the shortwave channel. March 2000 provided the initial ratio of shortwave measurements for the FM1 instrument and is shown in figure 2. Again, these linear correlations are very good, r^2 is 0.998 and the variance is $1.200 \text{ (watt/m}^2\text{/str)}^2$ which are typical values for all months processed. Continuing this process monthly, this ratio is plotted as a function of time. Illustrated in figure 3, the ratio has been increasing for both instruments since the beginning of the mission where the initial ratios matched ground calibration measurements, although the drift in FM1 seems to start later, in early 2001. The drift is more severe in FM2, increasing 2.5 percent of the initial ratio of the shortwave portion of the total sensor to the shortwave sensor.

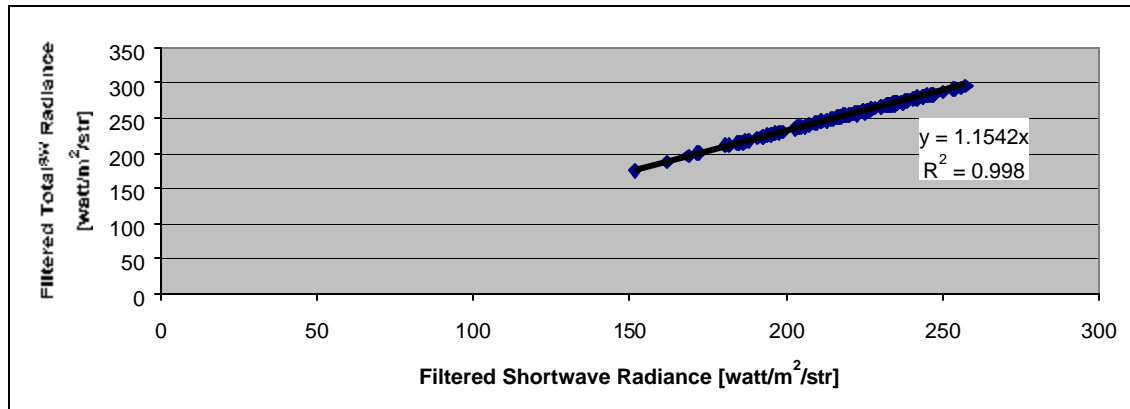


Figure 2: Correlation between filtered shortwave radiance and the shortwave portion of the filtered total radiance for daytime DCC in March 2000 detected by FM1.

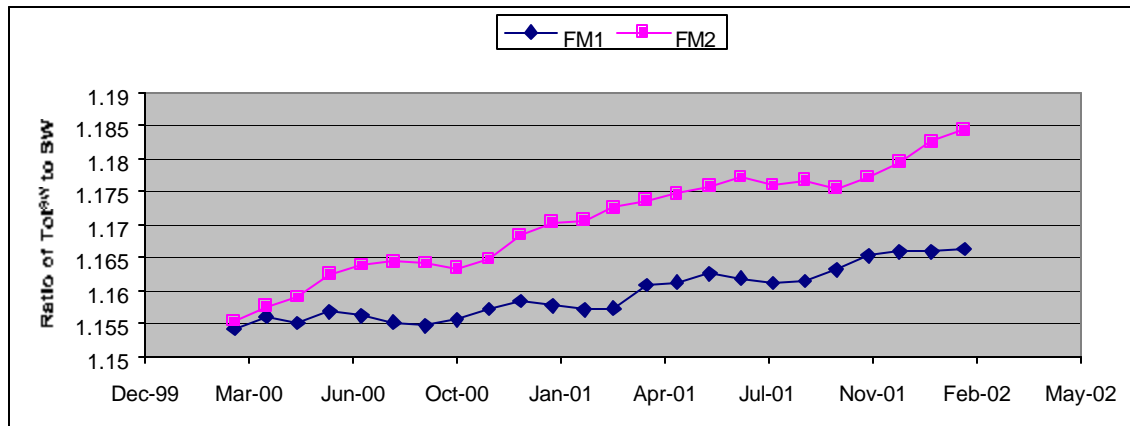


Figure 3: Trending of the ratio of the shortwave portion of the filtered total sensor to the filtered shortwave sensor using the three-channel inter-comparison.

A second three channel inter-comparison trending analysis is monitored also. As with estimating the shortwave portion of the total sensor detector, this inter-comparison uses DCC footprints for the measurements and is performed on a monthly basis. However, instead of training the nighttime window radiance to the nighttime total radiance, the window measurements are trained to the unfiltered longwave derived from the filtered measurements from the three sensors. The correlation coefficients are used to obtain derived unfiltered longwave radiance for daytime using the daytime filtered window radiance. The difference between the derived and measured daytime unfiltered longwave radiance is linearly correlated to the filtered shortwave measurement again with a forced zero intercept. A trend plot of the slope of the correlation between the filtered shortwave and the delta longwave over the life of the mission is shown in figure 4.

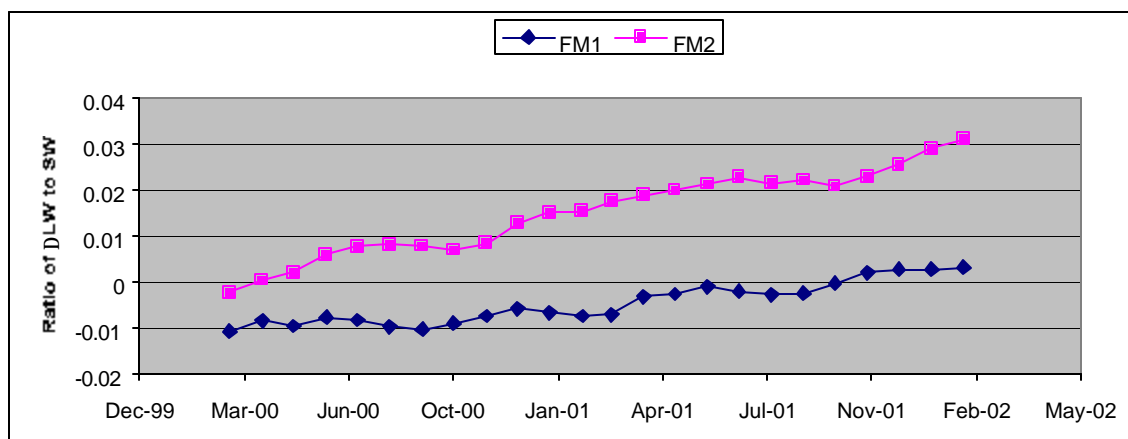


Figure 4: Trending of the ratio of the delta longwave to the measured shortwave channel using the three-channel inter-comparison.

The daytime correlations are quite noisy with the variance often greater than 50 percent of the delta longwave and low correlation coefficients. However, the shortwave and delta longwave should not correlate especially since delta longwave should tend to zero. This still serves as a good trending analysis since nonzero results may indicate a problem. The nighttime correlations are very steady over mission life. Nighttime correlations are stable with time both between filtered window radiance and filtered total radiance and also between filtered window radiance and unfiltered longwave radiance, figure 5.

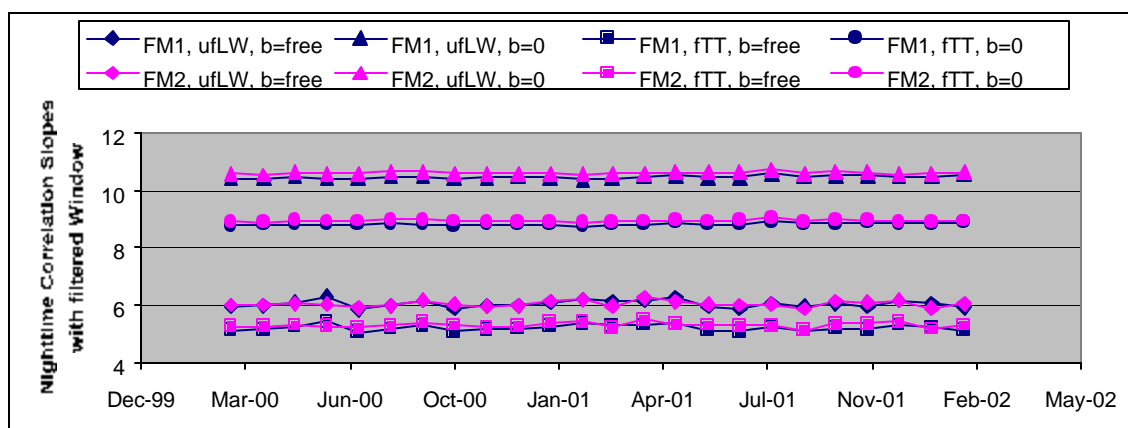


Figure 5: Resulting slopes of the nighttime linear correlations between filtered window sensor radiance and the filtered total sensor radiance and between the filtered window sensor radiance and unfiltered longwave flux. b=0, indicates that the intercept was fixed equal to 0. b=free, indicates the intercept was non-fixed. uLW = unfiltered longwave, fTT = filtered total

2.2 Direct Comparison

The CERES instruments scan from the limb of the Earth on one side of the instrument to the Earth's limb on the opposite side of the instrument and return. One scan takes 6.6 seconds. Each instrument has two nadir footprints, zero viewing zenith angle with respect to the footprint, per scan. The direct comparison analysis pairs the two nadir views of each instrument that are within 1.65 seconds of each other, one quarter of the scan period. These coincident nadir measurements of the two instruments are differenced (FM2 - FM1) and averaged per month based on scenes. The trending of the daytime longwave flux differences is shown in figure 6 for various scene types.

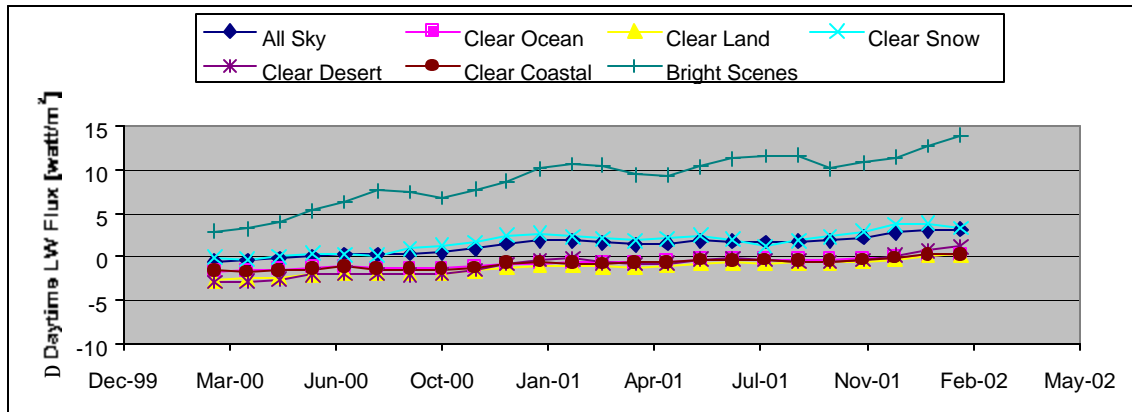


Figure 6: FM2-FM1 difference for daytime longwave flux over mission life for all sky conditions, various clear scenes, and bright scenes.

Bright scenes are defined as scenes with filtered shortwave radiance greater than $200 \text{ watts/m}^2/\text{str}$ detected by the FM1 instrument. In addition, all logic used in this analysis, such as scene type and cloudiness, is based on what was detected by the FM1 instrument. The trending of the nighttime longwave flux direct comparison is shown in figure 7 and daytime shortwave flux trending is plotted in figure 8.

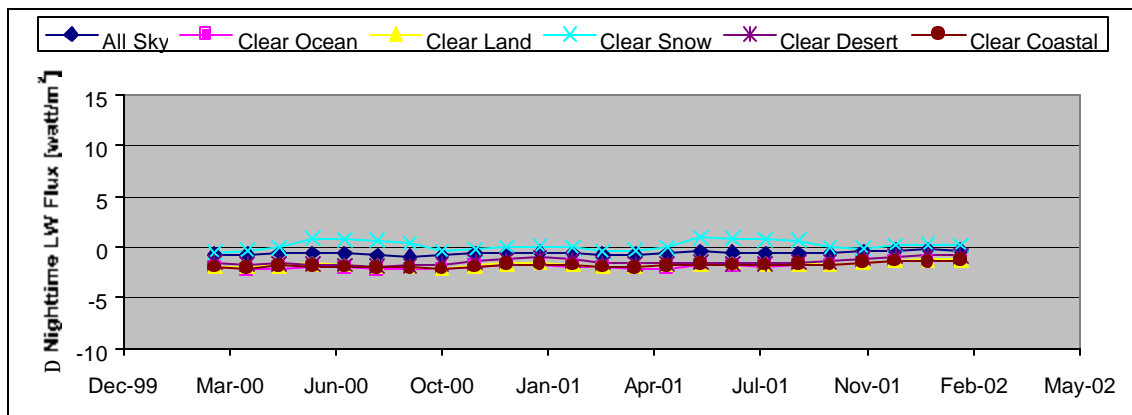


Figure 7: FM2-FM1 difference for nighttime longwave flux over mission life for all sky conditions and various clear scenes.

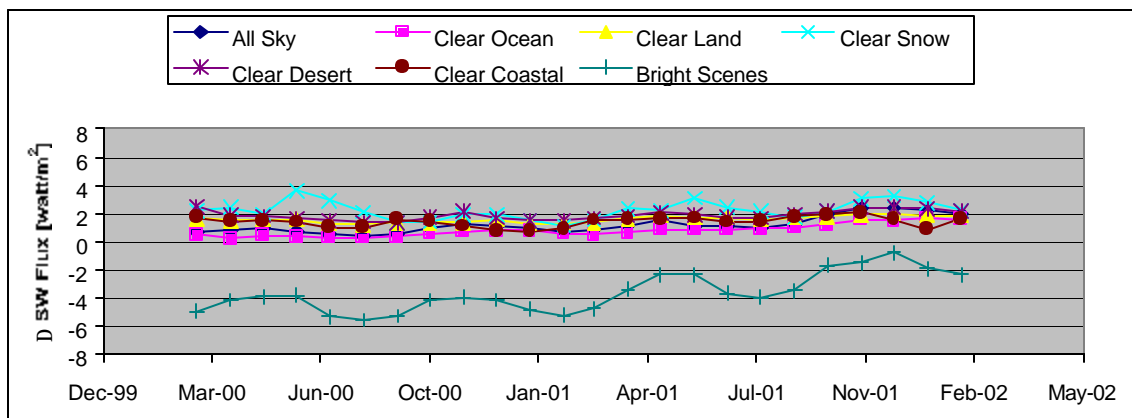


Figure 8: FM2-FM1 difference for daytime shortwave flux over mission life for all sky conditions, various clear scenes, and bright scenes.

A horizontal trend line indicates the sensors of the two instruments are stable with respect to each other. However, the two sensors could be drifting at the same rate and the direct comparison would not indicate a drift since equal trending between the two sensors subtract out. Comparisons between these trending plots indicate that the drift is in the shortwave region of the measurements. The nighttime longwave flux does not indicate any significant change between the two instruments over mission life. However, the daytime longwave flux shows a continuous drift in average values between the two instruments over time. This is more pronounced in the bright scene averages where the difference between the two instruments is greater in magnitude, and that difference grows with time. The daytime shortwave fluxes show little drift in average value between the two instruments except, again, for the bright scenes. Further, the drift appears to begin after March 2001, and the shape of the curve looks similar to the three-channel inter-comparison results for FM1 (figures 3 and 4).

3. DISCUSSION

Gain coefficients are used to convert CERES measurements from electronic count values to radiance units. These coefficients are determined during ground calibrations of the instruments.⁴ Once in flight, on-board calibrations are performed weekly to reassess the gain. Figure 9 shows the history of the percent deviation from the ground derived gain coefficients determined from on orbit calibrations for the three sensors on both instruments. Over mission life, the gains of the total channel sensors for both CERES instruments have increased while the window and shortwave sensor gains have remained somewhat constant although the window sensors are quite noisy.

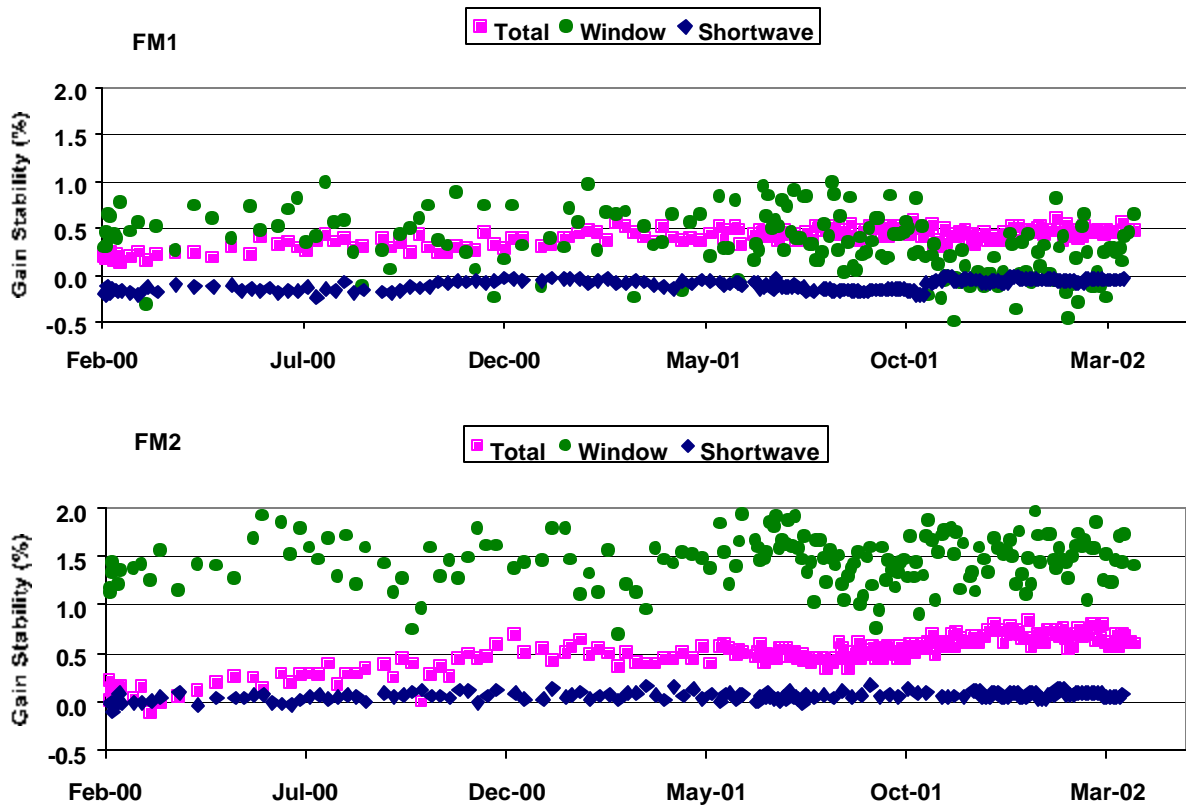


Figure 9: Percent deviation from ground derived gains during on orbit calibrations for all three sensors of both instruments.

The three-channel inter-comparison shows that the ratio of the shortwave portion of the total channel sensor to the shortwave channel sensor is increasing with time (figure 3). This drift is more pronounced in the FM2 instrument and initiates at the beginning of the mission. The drift in the FM1 instrument is less and

appears to initiate after March 2001. The direct comparison shows that the average difference of coincident daytime longwave nadir measurements between the two instruments is increasing in time, figure 6. Trending plots do not show a drift in nighttime longwave measurements (figures 5 and 7). The window channel sensor is stable in time during both daytime and nighttime. Internal calibrations do not show drift in shortwave channels. Thus, the shortwave portion of the total channel sensor may be too responsive causing the total channel to read high and this mis-reading is increasing with mission time. The daytime unfiltered longwave radiance and flux are derived in part by subtracting the shortwave sensor value from the total channel sensor value. If the total channel errs falsely high, the resulting longwave value will be falsely high for daytime when shortwave values are nonzero. When shortwave is zero during nighttime, the drift is not detected by these analyses.

Mean longwave radiances over the tropical ocean remain very stable over time with a mean variation of about 0.7 percent over a 5 year period. This has been shown by measurements taken by the Earth Radiation Budget Satellite (ERBS) instrument.⁵ Thomas⁶ applied this technique to the CERES instruments on Terra and found that the daytime minus nighttime differences between monthly averaged longwave unfiltered radiances has increased about 0.25 percent from March 2000 to December 2001 for the FM1 instrument. The drift in the FM2 instrument was about 1 percent. This is consistent with the findings here and indicates drifting of CERES instruments' measurements is occurring in the shortwave region. Also, it is consistent that FM2 has a larger drift.

4. DRIFT CORRECTION

4.1 Correcting drift using ground software

An attempt to correct the drifting of the CERES instruments on Terra has been made using ground software. By reducing the gain in the total channel sensor with time, it is hoped to reduce and thus, correct the total channel sensor measurements. A numerical scheme was devised to reprocess raw CERES data from beginning of the mission with gain coefficients linearly adjusted with time over mission life. In addition, the spectral response functions were also incorporated into the scheme to spectrally filter the shortwave portion of the total channel sensor. As with the gain coefficient adjustment, the spectral response function was made to linearly vary with time over mission life. Every other month of FM1, FM2 raw data was reprocessed starting with March 2000 to December 2001 with linearly varying gains and spectral response functions. January and February 2002 were included also. Although the software was written to apply time varying gain and spectral response functions to all three sensors, only the total channel for both instruments was applied time varying gain coefficients. No time varying spectral response functions were applied to the FM1 instrument.

4.2 Three-Channel Inter-comparison Using Deep Convective Clouds

The three-channel inter-comparison was used to trend the ratio of the shortwave portion of the total channel sensor to the shortwave sensor. As seen in the results plotted in figure 10, there is an improvement in that some of the drift has been reduced, however, the drift was not eliminated.

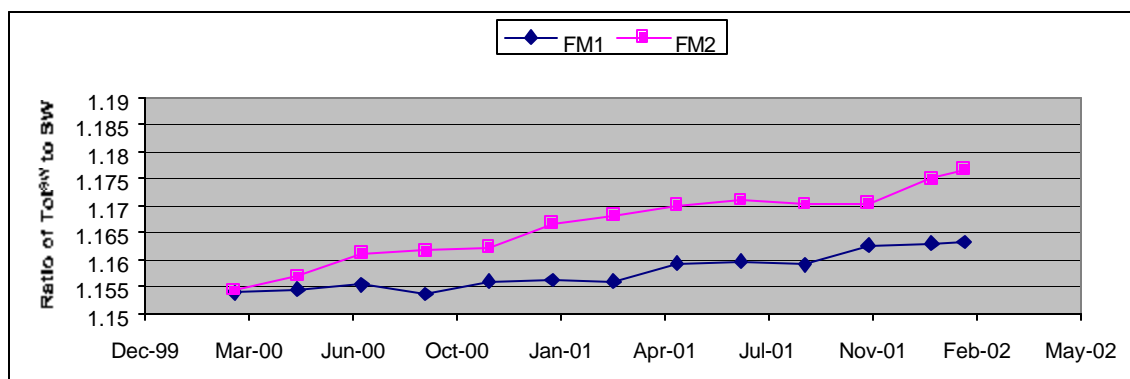


Figure 10: Trending of the ratio of the shortwave portion of the filtered total sensor to the filtered shortwave sensor using the three-channel inter-comparison implementing corrections to gains and spectral response functions.

The improvement of the three-channel inter-comparison using unfiltered radiances (figure 11) is pronounced. The drift in ratio of delta longwave to shortwave in FM2 is removed. No change in spectral response functions was applied to the FM1 instrument, so the improvement here is due solely to time varying gain coefficients in the total channel sensor.

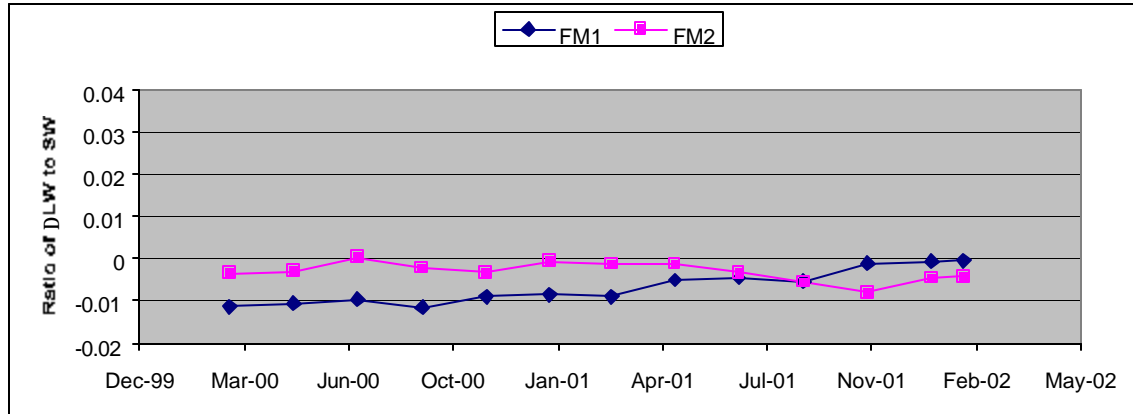


Figure 11: Trending of the ratio of the delta longwave to the measured shortwave channel using the three-channel inter-comparison implementing corrections to gains and spectral response functions.

4.3 Direct Comparison

When directly comparing coincident nadir measurements, the daytime longwave differences, figure 12, show the most improvement with the time varying drifts and spectral corrections. The apparent over correction after March 2001 is probably due to the remaining drift in the FM1 instrument driving the difference down since the FM1 measurement is subtracted from the FM2 measurement.

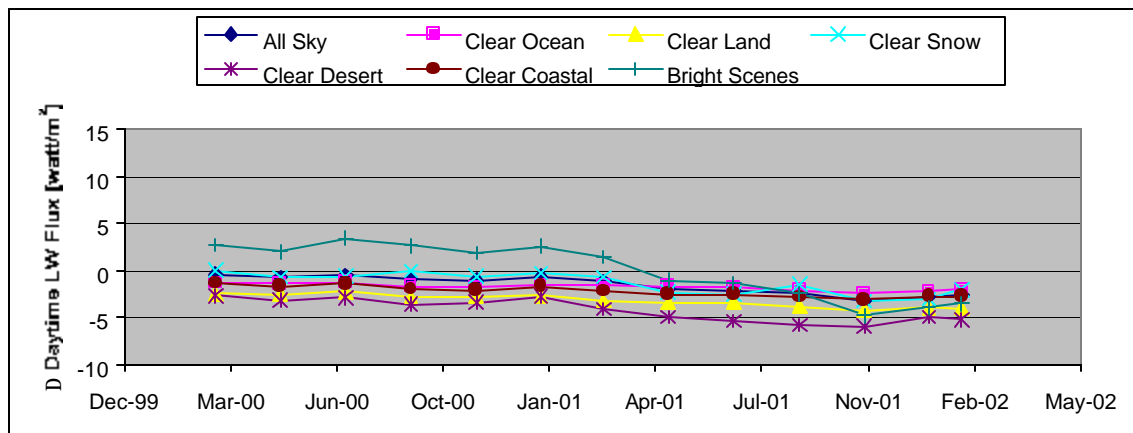


Figure 12: FM2-FM1 difference for daytime longwave flux over mission life for all sky conditions, various clear scenes, and bright scenes after corrections to gain and spectral response functions.

The nighttime longwave differences, figure 13, are about the same as previous, figure 7. The shortwave flux shown in figure 14, is not much improved over the previous results, figure 8. Additional work needs to be done to remove the drift from the FM1 instrument.

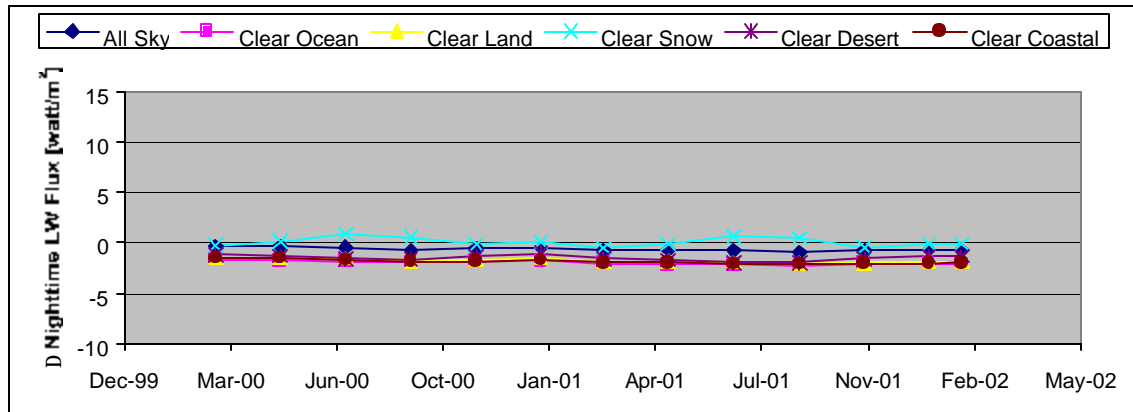


Figure 13: FM2-FM1 difference for nighttime longwave flux over mission life for all sky conditions and various clear scenes after corrections to gain and spectral response functions.

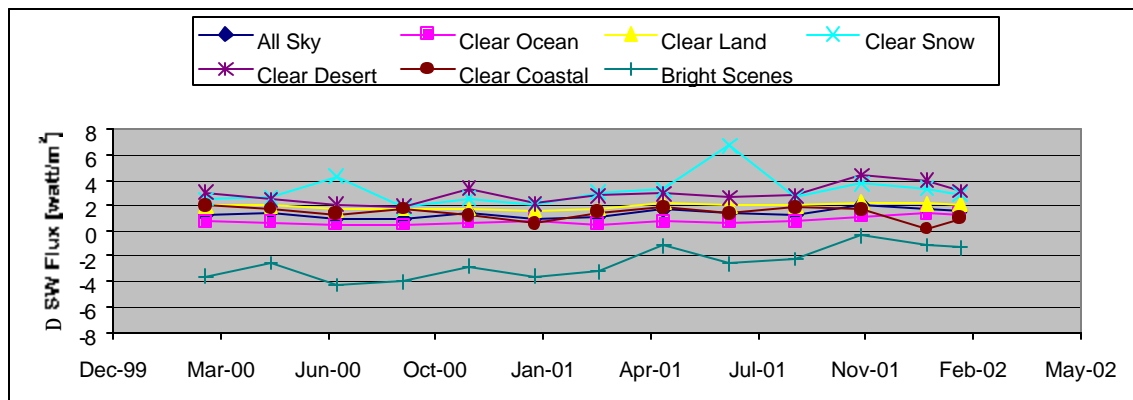


Figure 14: FM2-FM1 difference for daytime shortwave flux over mission life for all sky conditions, various clear scenes, and bright scenes after corrections to gain and spectral response functions.

Shown in figure 15 is the delta longwave flux as a function of the shortwave flux measured by the FM1 instrument in March 2000 and February 2002. Values have been averaged in 10 watt/m² bins of shortwave flux values. Included is the February 2002 reprocessed values using the time varying gains and spectral response functions. At the beginning of the mission, there is an increase in the difference between the two instruments in longwave flux as the shortwave increases. This difference increases with mission life. The February 2002 corrected values lose this difference increase with intensifying shortwave flux. In fact, the difference appears to decrease.

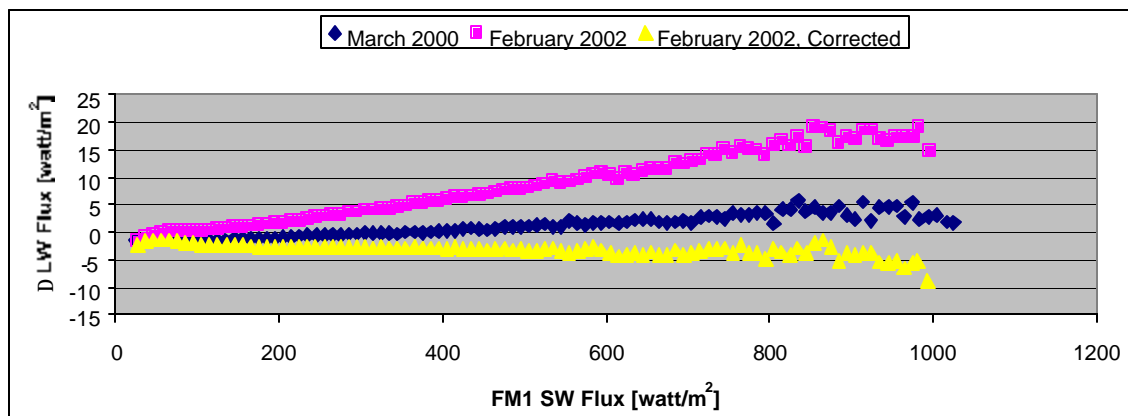


Figure 15: FM2-FM1 difference for daytime longwave flux as a function of the shortwave flux from the FM1 instrument for March 2000 and February 2002. Also, February 2002 after corrections to gain and spectral response functions.

There does not appear to be much drifting in the shortwave flux difference as a function of shortwave flux with time, figure 16.

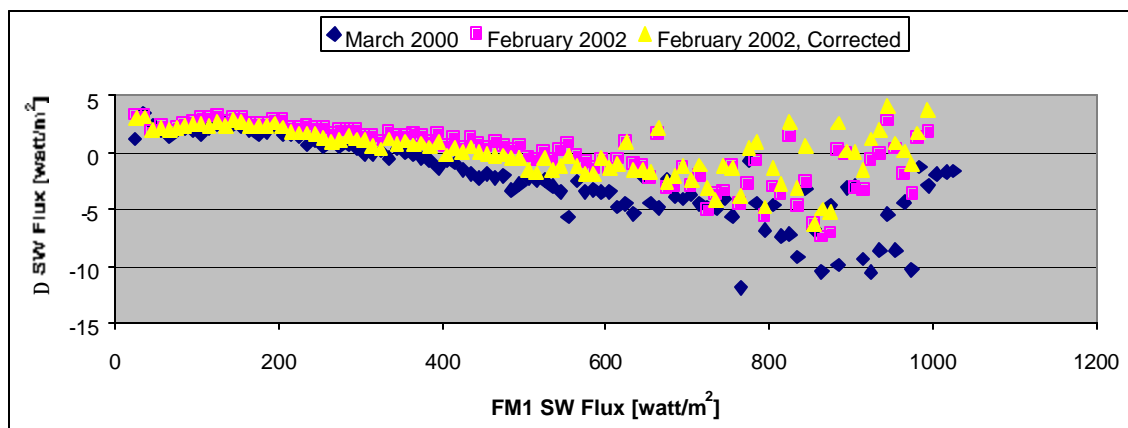


Figure 16: FM2-FM1 difference for daytime shortwave flux as a function of the shortwave flux from the FM1 instrument for March 2000 and February 2002. Also, February 2002 after corrections to gain and spectral response functions.

The time varying drift and spectral response have improved the daytime longwave values, figure 17. The February 2002 corrected results are much closer to the values at the beginning of the mission in March 2000.

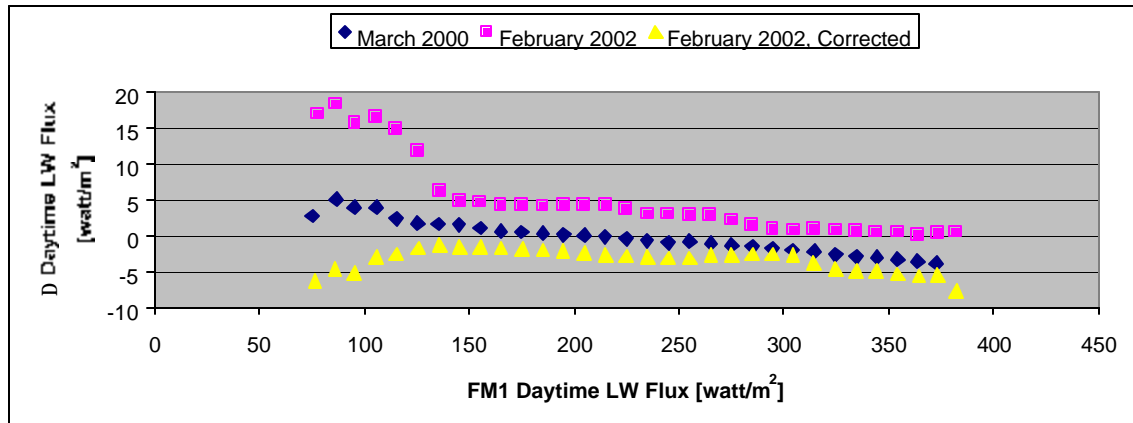


Figure 17: FM2-FM1 difference for daytime longwave flux as a function of FM1 longwave flux for March 2000 and February 2002. Also, February 2002 after corrections to gain and spectral response functions.

5. CONCLUSIONS

Analyses have been developed using ground based software to aid in monitoring the stability of the CERES instruments' radiance measurements in space. The three-channel inter-comparison is used to detect inconsistencies between the three sensors. The direct comparison can detect inconsistencies between coincident measurements between the two instruments. Implementing these analyses on the CERES instruments on the Terra satellite has shown that the ratio of the shortwave portion of the total channel sensor to the shortwave sensor is increasing with time, especially in the FM2 instrument. The direct comparison showed that the differences between instruments mainly in daytime longwave values are increasing with time. It is believed that the shortwave portion of the total channel sensor is reading high for the FM2 instrument. Also, the FM1 instrument may be reading low in its shortwave sensor. Initial attempts to correct these drifts using ground software show good promise. Additional work needs to be done to isolate the causes of drift in the CERES detectors and more exact methods of removing the drift using ground software.

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